CHARACTERISATION AND MODELLING OF AIRFIELD PAVEMENT STRUCTURES FOR TOMORROW'S EXTRA LARGE AIRCRAFT

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Abstract:

Multi layer linear elastic systems have been used for many years for the design of airfield pavements and the analysis of the damaging effect of complex multiple wheel configurations. Normally the peak tensile strain at the bottom of the asphalt layer is taken as one of the design criteria and the number of peak strain repetitions is used as input for a fatigue analysis. The problem with this approach is that with multiple wheel configurations it is not clear whether one should take into account the number of strain peaks as number of load repetitions or the number of gear passes. Another problem with such analyses is that pavement materials are certainly not linear elastic, they are non linear elasto-visco-plastic. This behaviour should be taken into account especially since tomorrow's heavy aircraft will generate high stresses and strains in the pavement layers.

In this paper a non linear elasto-plastic model is presented for asphalt mixtures that allows damage in pavement layers, expressed in terms of plastic strain accumulation, to be calculated as a function of the material characteristics and the number of load repetitions. It is shown that the model parameters can be calculated from relatively simple uniaxial tension and compression tests.

It is believed that the methodology presented is a powerful tool to analyse the damaging effect of heavy multiple wheel gear loads on asphalt pavements.

Introduction:

The design of flexible airfield pavements is usually based on an analysis of the stresses and strains that occur in the pavement layers as a result of the aircraft loads which are expected, and the comparison of these values with the allowable ones. The allowable stresses and strains are based on results from e.g. fatigue tests performed on asphalt mixtures or repeated load triaxial tests performed on unbound granular materials. The stress – strain analyses are commonly made using a computer programme for multi layer linear elastic isotropic structures.

Although many airfield pavement specialists admit that this approach implies that crude simplifications of reality are made, one also admits that until now this approach has resulted in satisfactory designs. The question however is whether this will still be the case when designing new pavements or when the quality of existing pavements has to be evaluated when they are loaded with tomorrow's heavy aircraft with complex wheel configurations. It is believed that for those cases better models are needed to determine where damage will initiate and how it progresses as a result of such heavy loads. This improved knowledge is, amongst other things, needed in order to determine whether materials with enhanced characteristics are required and to make realistic performance evaluations of existing materials and structures.

Some of the questions that need an answer are, e.g. "How do we determine the ACN of such aircraft and how do we determine the damaging effect of various aircraft when compared with each other?"

The determination of e.g. the ACN has been subject to intensive debate in ICAO's working committee ACN/PCN. The committee has not yet been able to come up with a feasible answer simply because one realises that the traditional approach is only partly useful to solve these questions.

World wide, research is therefore underway to develop improved damage initiation and progression models using non linear elasto-visco-plastic approaches. This paper describes the developments that are made at the Delft University of Technology in the Nether-lands in this field.

The first part of the paper will however deal with a description of the analysis techniques which are more or less common practice and it discusses the drawbacks of these approaches.

Discussion of some currently used analyses techniques:

One of the big disadvantages of the commonly used approaches is the very simplistic way in which damage is analysed especially in case of complex multiple wheel loads.
Figure 1 e.g. shows the tensile strain at the bottom of a 250 mm thick asphalt layer (E = 4000 MPa) on top of a 300 mm base (E = 300 MPa) on top of a subgrade with E = 100 MPa. Three single 250 kN wheel loads (radius loaded area = 200 mm, centre to centre distance 1000 mm) are applied on the layered system.

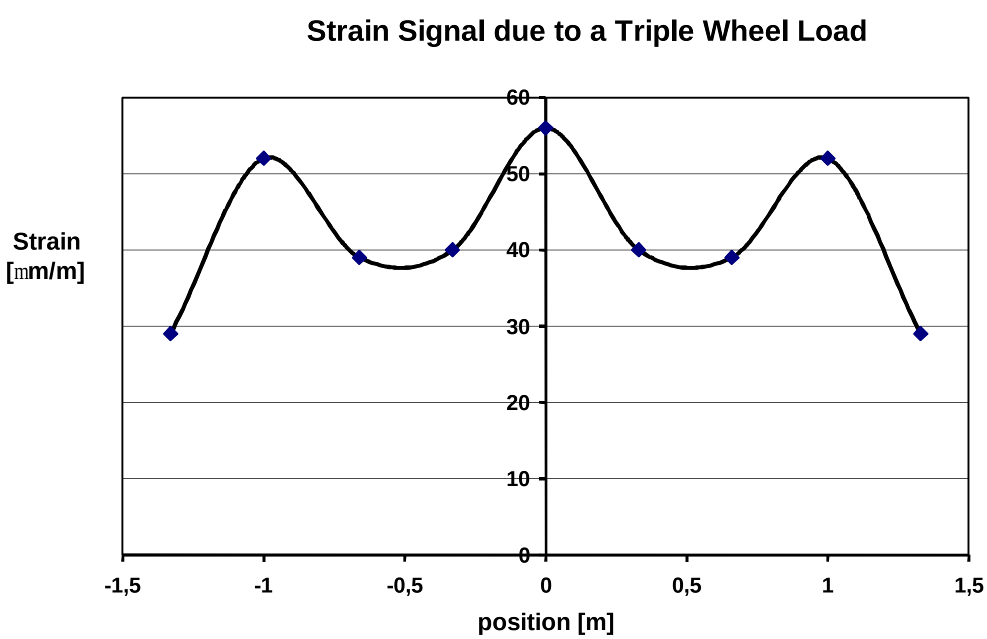

Figure 1: Strain signal due to a triple wheel load.

Although three distinct peak values can be observed, the question is whether they should be taken as three load repetitions of around 55 μm/m or whether they should be taken in-to account in a different way. The answer is of course that one should take into account the entire signal because this is causing the damage and not three individual peak values but how should that be done?

A solution could be to do a linear visco-elastic analysis since then the amount of energy that is dissipated can be calculated from the stress and strain signal and fatigue failure models based on the amount of dissipated energy can be used to determine the pavement life. Such a procedure has been proposed by Stet e.a. [1]. Linear visco-elastic models like VEROAD [2] can be used for such analyses; dissipated energy based fatigue models were first proposed by van Dijk e.a. [3].

One major disadvantage that still remains is that the entire analysis is still linear. It is expected that this might be not realistic for the extra large aircraft with their complex wheel configurations. The stresses caused by these aircraft might be so high that the material starts to behave non linear. This is especially the case for pavements containing a large body of granular materials.

An example of the effects of non linear behaviour is shown in figures 2 and 3. Figure 2 shows the variation of the modulus over the height of the unbound base due to a 75 kN load (radius of the loading area is 150 mm). Figure 3a shows the variation of the ratio of the occurring maximum principal stress to the maximum principal stress at failure, while figure 3b shows the variation of this ratio over the height of the base when the same pavement is loaded with a 250 kN wheel load (radius of the loading area is 240 mm).

Note that the asphalt layer is assumed to behave linear elastic while the stiffness of unbound base and sand subbase is assumed to be stress dependent including a stress hardening at low stress levels and softening at high stress levels. Information on the stress dependent behaviour was taken from [4]. The behaviour of the subgrade was again assumed as linear elastic. The calculations for figures 2 and 3 were made using the axi-symmetric finite element programme NOLIP [5].

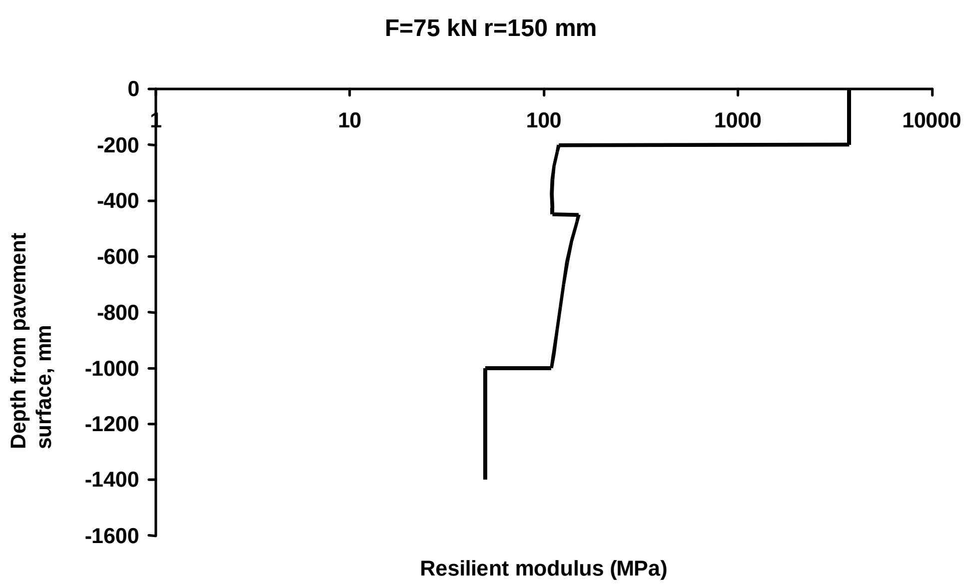

Figure 2: Variation of base and sand subbase modulus with depth for the 75 kN load.

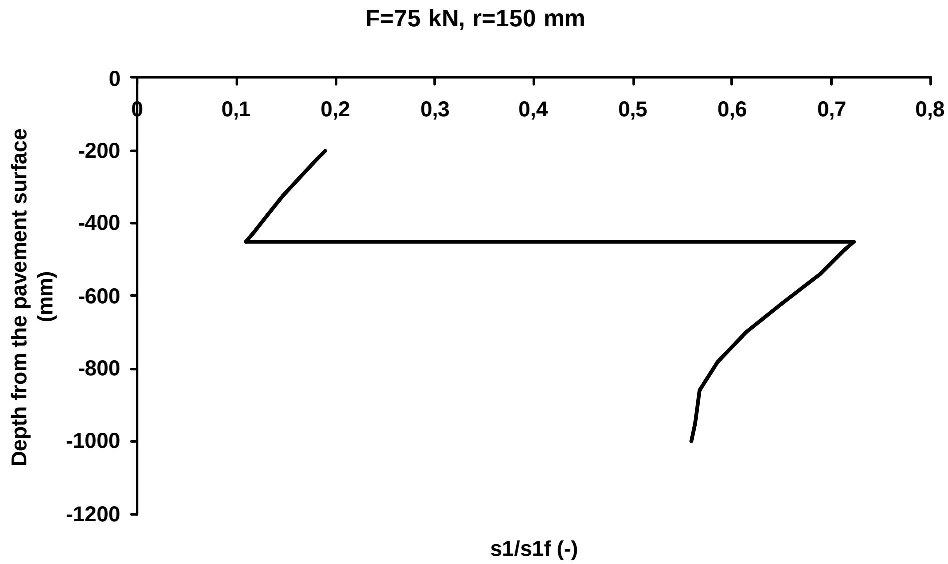

Figure 3a: Ratio of occurring maximum principal stress to maximum principal stress at failure at the prevailing confinement for the 75 kN load.

Finally damage progression and the effect of that on the redistribution of stresses and on the performance of the pavement is not taken into account in the commonly used procedures. In these procedures the stresses and strains are calculated from the initial conditions and the effects of damage progression on e.g. the stiffness of the asphalt mixture is more or less taken into account through the fatigue relation used.

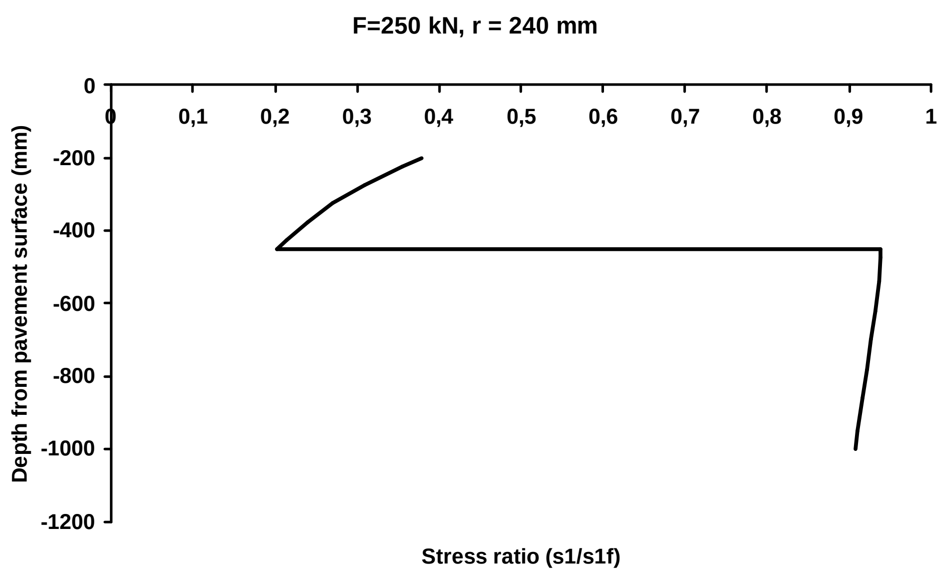

Figure 3b: Ratio of occurring maximum principal stress to maximum principal stress at failure given the prevailing confinement for the 250 kN load.

For these reasons research is underway at the Delft University into the characterisation of the behaviour of materials under a 3D state of stress and the initiation as well as progression of damage in pavements. The research currently concentrates on the behaviour of asphalt mixtures being the most costly material in flexible pavements. This paper describes the results obtained so far and shows how the models developed can be used in damage predictions for airfield pavements loaded by complex wheel configurations of heavy aircraft.

Non linear elasto-visco-plastic modelling:

In order to arrive at a better understanding of the damage mechanisms in asphalt concrete it is necessary to establish more fundamental knowledge about the material properties and response. In that response, influence factors like temperature and strain rate must be considered. Furthermore, it must be realised that to truly investigate the material behaviour, structural influences on the observed response should be prevented. Tests e.g. should be designed with their potential problems in mind, trying to establish uniform internal states of stress.

At this moment the Finite Element Method is used in many related engineering material fields to study the influence of the material properties on the structural response. This numerical method offers the possibility to actually look inside the structure in order to wit-ness the damage mechanisms that occur, which will generate new insight in those mechanisms. The understanding of these mechanisms will enable the improvement of design methods, which will lead to better roads and a reduction in maintenance.

A pre-requisite for the use of the Finite Element Method is the availability of material models that can describe the triaxial behaviour in both the linear and non-linear range. For asphalt concrete such a model is not available at present. For this reason, a project was started at the Delft University of Technology to develop and implement a three-dimensional non-linear material model for asphalt concrete. The model will incorporate all aspects of asphalt material behaviour, elasticity, visco-plasticity and cracking and it will be implemented in the Finite Element Package CAPA-3D [6]. The model that was selected after an extensive literature survey is the model proposed by Desai [7].

The Delft University ACRe-model (Asphalt Concrete Response) uses the flow surface proposed by Desai [7] in combination with a set of constitutive relations developed to facilitate the description of asphalt concrete response. In broad outlines, the model works as shown in figure 4. This figure compares the one- and two-dimensional situation. Originally, the behaviour is linearly elastic, represented by the straight line until point 1 in the left-hand diagram. From point 1, which corresponds to ellipse 1 in the 2D case, the response is non-linear but the load carrying capacity can still increase. This response is commonly known as hardening and in the 1D case it looks as a curve with diminishing slope (between points 1 and 3). In the 2D case this phase of response corresponds to a series of successive, in size increasing, ellipses (1 to 3). The strength (the maximum, point 3) in the 1D situation corresponds to the largest ellipse in the 2D case. After this point the strength decreases (softening), which is illustrated by the descending branch in the 1D diagram (between point 3 and 4). In the 2D case this again corresponds to series of successive ellipses, this time diminishing in size. A material model consists of the shape and size of the flow surface (the ellipse), the relations which describe the changes in shape and size (the successive ellipses) and the relations between stresses and strains inside the ellipse at each stage (within the first ellipse this would be Hooke's law).

In the elastic region the constitutive relation is:

$$\underline{\sigma} = \mathbf{D}\underline{\varepsilon} \tag{1}$$

In which $\underline{\sigma}$ is the stress vector, $\underline{\varepsilon}$ the strain vector and **D** the elasticity matrix. Equation (1) is the three dimensional form of Hooke's law. As long as the state of stress is such that the material is not damaged, this relation describes the deformations. Once the material response becomes inelastic, the material exhibits remaining deformations. This damage can be cracking and/or plastic deformations, based on the constitutive relations that are used. Consequently, the model is capable of predicting and describing combinations of failure mechanisms, such as rutting and cracking. In the inelastic region, the strains are decomposed into several components:

$$\varepsilon = \varepsilon_e + \varepsilon_i = \varepsilon_e + \varepsilon_p + \varepsilon_{cr} \tag{2}$$

Where e_e is the elastic strain and e_i the inelastic strain, which consists of a cracking (e_{cr}) and a plastic component (e_p). Since the stresses in a material are related to the elastic strains, the constitutive relation in the inelastic region becomes:

$$\underline{\sigma} = \mathbf{D}\underline{\varepsilon}_e = \mathbf{D}\left(\underline{\varepsilon} - \underline{\varepsilon}_p - \underline{\varepsilon}_{cr}\right) \tag{3}$$

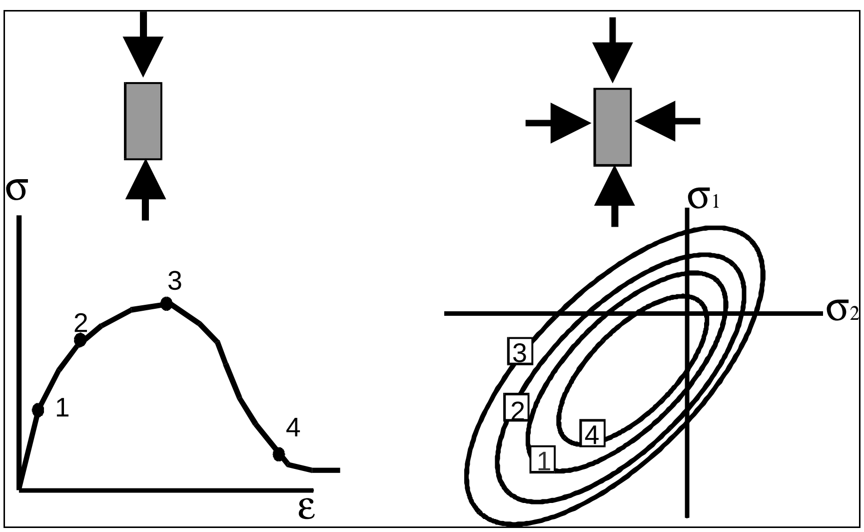

Figure 4: The principle of a material model for the 1- and 2-dimensional case. The numbered points in the 1D diagram correspond to the ellipses in the 2D case.

Whether the material is damaged by a specific state of stress depends on the flow surface:

$$f = \frac{J_2}{p_a^2} - \frac{\left[-a\left(\frac{\left(I_1 - R\right)}{p_a^2} \right)^n + g\left(\frac{\left(I_1 - R\right)}{p_a^2} \right)^2 \right]}{\sqrt{1 - b\cos\left(3q\right)}} = 0 \qquad (4)$$

For:

$f < 0 \Rightarrow$ *elastic behaviour, the material is not damaged ,*

$f = 0 \Rightarrow$ *inelastic behaviour, the material gets damaged*

With: *J2* is the second deviatoric stress invariant
I_1 is the first stress invariant
q is Lode's angle
p_a is the atmospheric pressure
a, b, g n and R are the model parameters

The stress invariants describe the state of stress that is evaluated and the model parameters control the size, shape and position of the flow surface. Since the flow surface controls what states of stress damage the material, the model parameters actually control the response to the state of stress that is applied. Because the material response for asphalt concrete depends on the temperature and loading rate, the model parameters can be ex-pressed as a function of these influences. The effect of the individual model parameters is illustrated in figure 5.

In figure 5, (A) shows the influence of a, the hardening parameter, which controls the size. For α=0, the surface becomes a straight line. Figure 5 (B) shows the effect of n, which is related to the onset of dilatation, figure 5 (C) shows how $b$controls the shape of the cross-section on the π-plane, which varies from circular to triangular. Finally in figure 5 (D) the way in which g determines the ultimate slope of the surface is illustrated.

The fifth model parameter, R, is the triaxial tensile strength. This parameter determines the position of the flow surface, since R is the intercept with the positive I_1-axis. For R=0, the material is cohesionless and the surface passes through the origin, while for higher R values the intercept shifts to the right. In all cases shown in figure 5, R is set to 2 MPa.

For a given asphalt mix each set of conditions (temperature and strain rate) corresponds to a set of model parameters. These original parameter values describe the elastic (damage initiation) limit for those conditions. The material degradation is incorporated in the model by changing some of the parameters as a function of the inelastic strains. The hardening (an increase of the area within the flow surface, figure 4) is described by decreasing a from its original value to zero. From figure 5a it can be seen that this leads to an open surface (straight line). Softening is modelled by decreasing the slope of this "ultimate response" line via a reduction of the original g value.

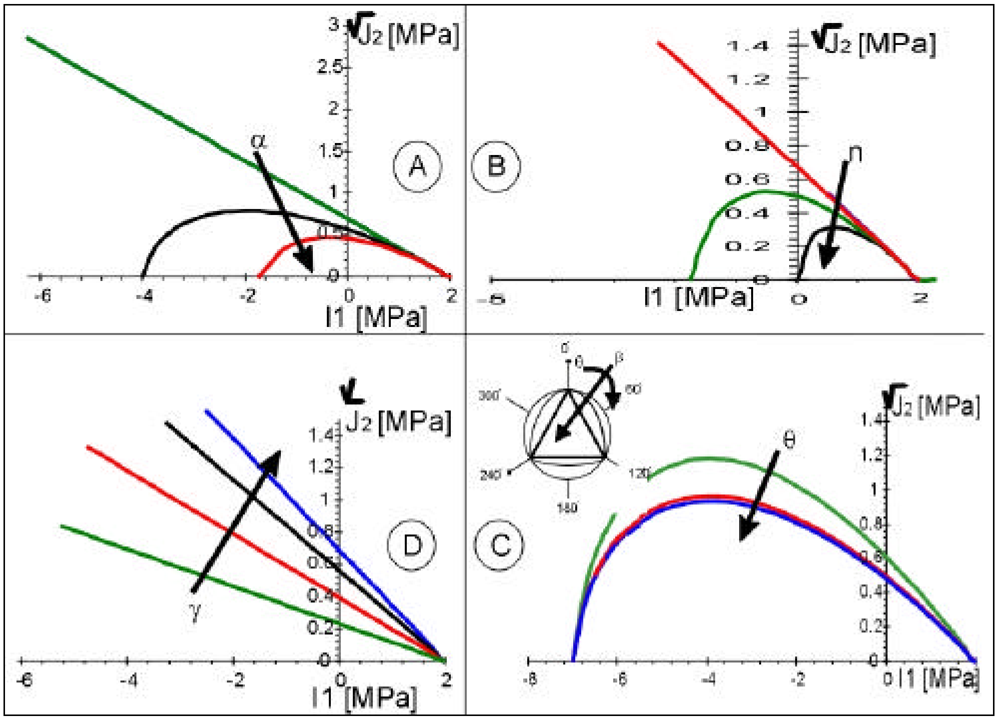

Figure 5: Influence of the model parameters on the size, shape and position of the flow surface in the I1-ÖJ2 surface.

More detailed descriptions of the model can be found in other publications [8, 9].

Tests that provide the model parameters:

The 3D material model described in the previous section provides a relation between stress and strain for any state of stress. Of course it is impossible to test all those states of stress, since the possibilities are infinite. Instead, a limited number of stress conditions is used in combination with a (mathematical) model that matches the expected material behaviour. Based on the states of stress that are tested, the model parameters are deter-mined. This means that the results from those test conditions are generalised to a full 3D surface on the basis of the characteristics of the model that you chose. In the ACRe project the material model is being developed along with an experimental programme that results in the required model parameters. The test programme involves amongst others uniaxial tension and uniaxial compression tests. The results from these two tests suffice for a first estimate of all model parameters except b(the first estimate of the 3D surface can be found from those test results). For the estimation of ba biaxial test is needed; experience has shown however that taking b= 0, is a reasonable first assumption.

A material model basically predicts the strain that results from a given state of stress. That prediction is based on the actually measured response to a limited number of states of stress, in tests. In order to get a reliable model, a sufficient number of stress conditions, preferably far apart in the 3D-stress space, is needed. Ideally, to determine the model parameters for a triaxiality, temperature and strain rate dependent material one would like to use triaxial tests at different temperatures and strain rates. On the other hand, knowledge on the uniaxial behaviour is very useful to get an impression of the capacity that is needed in triaxial testing. Furthermore, uniaxial tests are special cases of triaxial testing, since they can be considered triaxial tests with zero confinement. This means that they do provide information for the 3D material model. Since conventional triaxial test equipment originates from soil mechanics, it is not capable of applying tension-compression types of loading. These tension-compression states of stress are of particular interest, since they cause a lot of damage in asphalt pavements.

For this reason, it was decided to perform the multiaxial tests in the ACRe project not by means of a triaxial cell but with a four-point shear set-up that was developed during a previous project. This consideration, in combination with the fact that uniaxial compression and tension tests already provide a great deal of information on the model parameters, led to a test programme that included uniaxial compression and tension tests and well as multiaxial tests.

The uniaxial compression test:

Uniaxial compression tests have successfully been performed at different asphalt mixtures. A number of aspects are of importance to obtain reliable results. Lack of space doesn't allow to discuss these important aspects in detail. The interested reader is referred to [10] where a detailed description is given.

Figure 6 gives a picture of the test set up as used, an example of the test results obtained is given in figure 7.

Based on the test results an expression for the compressive strength as a function of strain rate and temperature was developed. Such a relation is necessary to generalise the results for use in a model that can be used to describe the response for conditions that were not tested. Before determining the relation some expectations about the general trend were formulated, which are shown underneath:

- **v=0**: **f_c=0**
- **v**® µ**:** the strength will not increase indefinitely, but reach a limit value: **f_c=C(T)**
- **T**® -µ**:** for extremely low temperatures, asphalt will exhibit glass-like, linear-elastic behaviour until sudden, brittle fracture occurs: **f_c=C^***
- **T** ® µ**:** for extremely high temperatures (approximately 160^{o}C) the bitumen will become a fluid: **f_c=0**

These considerations, which are discussed in more detail in [10], led to the expression shown in Equation (5).

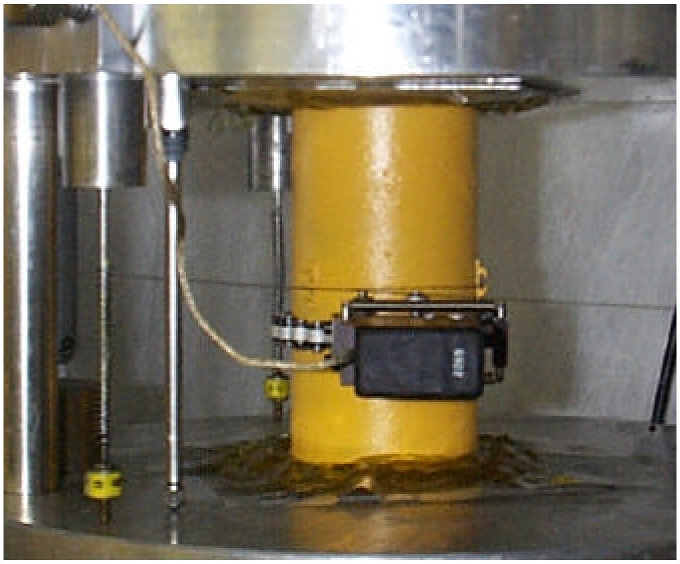

Figure 6: Close-up of the specimen in the compression set-up, showing the guidance bars and the instrumentation that registered the axial and radial deformations.

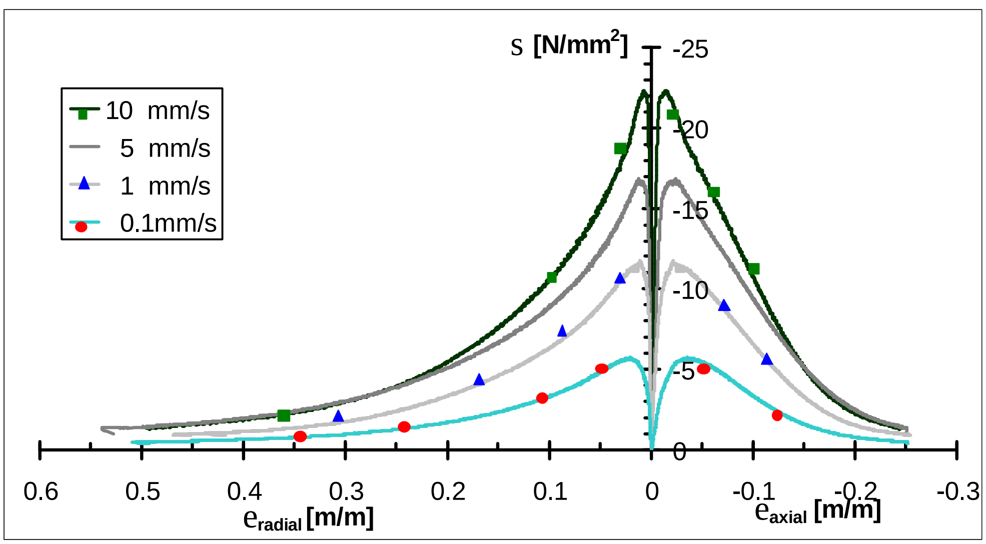

Figure 7: Average test results for 15°C.

$$f_c = -108\left(1 - \frac{1}{1+\left[\dot{e} \; {*}e^{\left(-86.3+\frac{24260}{T}\right)}\right]^{0.32}}\right) \tag{5}$$

f_c =*compressive strength in N/mm²*

$\dot{e}$ =*strain rate in* s^{-1}

T = temperature in Kelvin

$R^2 = 0.99$

A graphical representation of the test results and the strengths predicted by Equation (5) are shown in figure 8. The markers represent the individual test results and the lines show the predicted values.

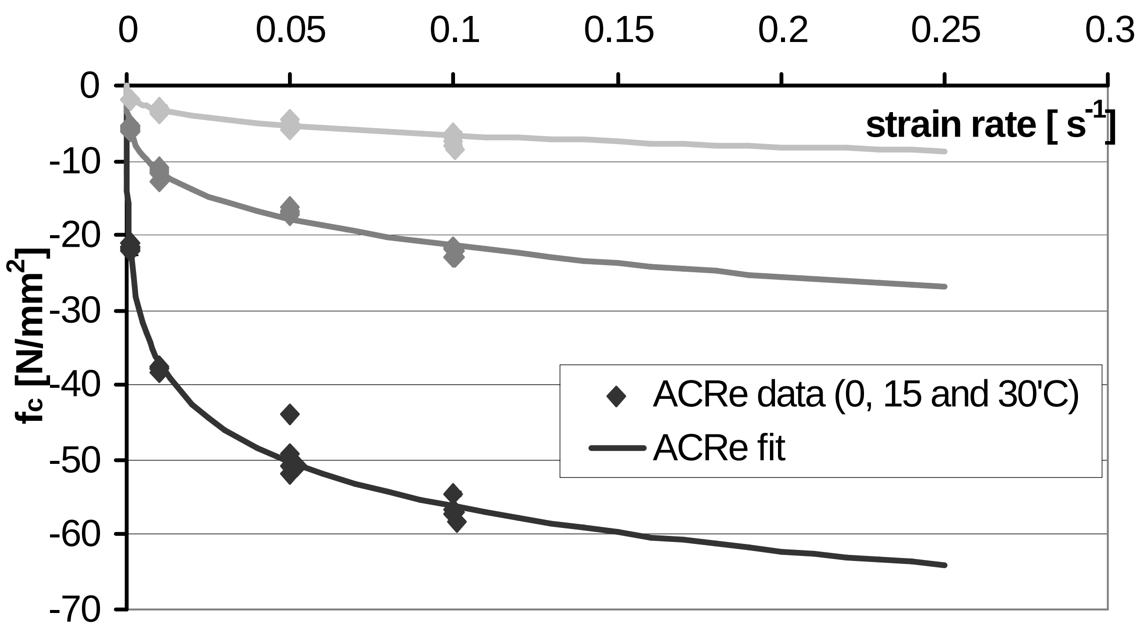

Figure 8: The individual data (markers) and predicted values (lines).

The uniaxial tension tests:

As mentioned before, also uniaxial tension tests are required in order to be able to calculate the values for the model parameters. The right hand side of figure 9 shows the test set up as used. The shape of the specimen was chosen such to ensure that the specimen failed at mid height. This was necessary to allow measurements to be taken on the energy release that occurs in the two halves that remain after failure. These measurements were done by means of strain gauges glued on the top and bottom half of the specimen.

The left hand side of figure 9 shows a simplified version of the tension test. This simplified version is needed because the parabolic type specimen is not useful for day to day testing. The simplified version allows testing to be done in any road material testing laboratory provided that a compression test frame of sufficient stiffness and adequate temperature control is available. The simplified version doesn't allow the energy release to be measured since it cannot be predicted on before hand where the specimen will fail. Figure 10 gives an example of the results.

Based on these results relations were developed which give the tensile strength as a function of strain rate and temperature. By using the results of both the compression and tension tests, the model parameters can be determined. Again lack of space to describe this process in detail; for a complete description the interested reader is referred to [11].

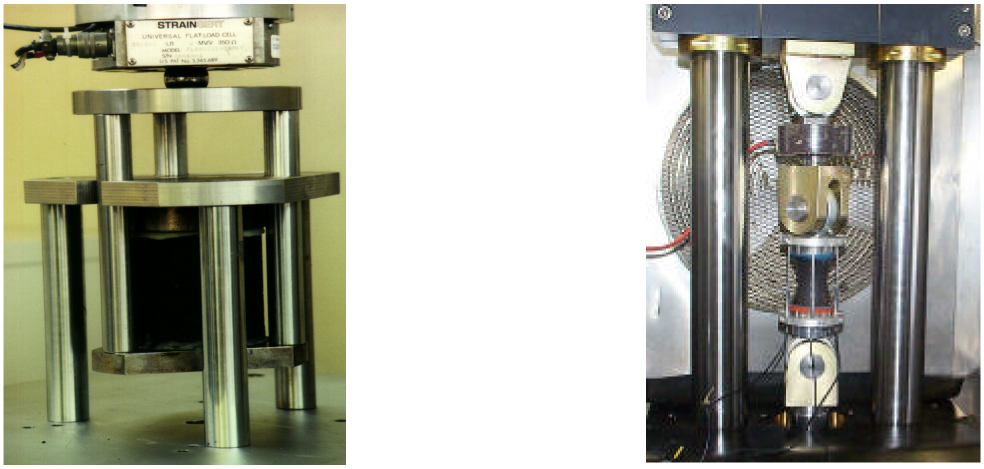

Figure 9: Tension test set up as used in the ACRe experiments (right hand side) and a simplified version.

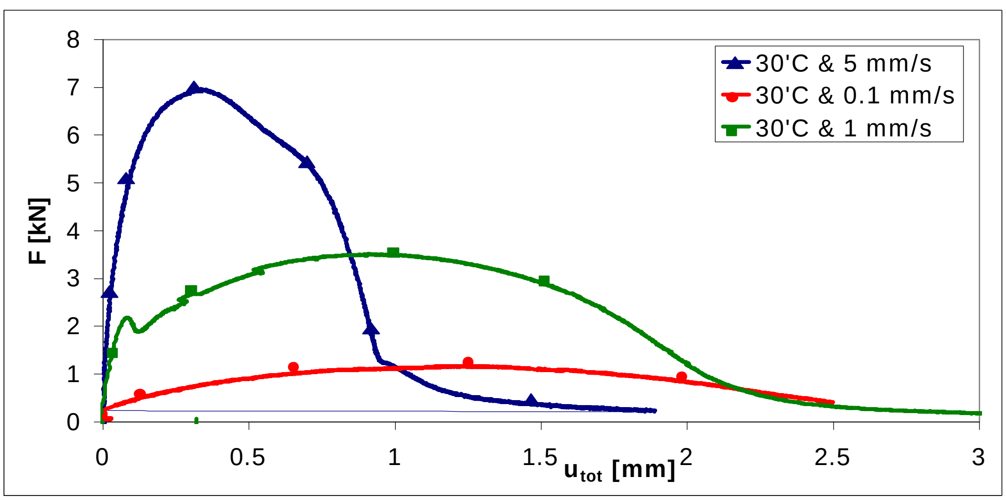

Figure 10: Example of the tension test results; note that the energy release after failure is not shown on the graph.

Model used for analysis of damage due to repeated loads:

The principle of a damage analysis due to repeated loads based on the information obtained from the uniaxial tests is schematically shown in figure 11.

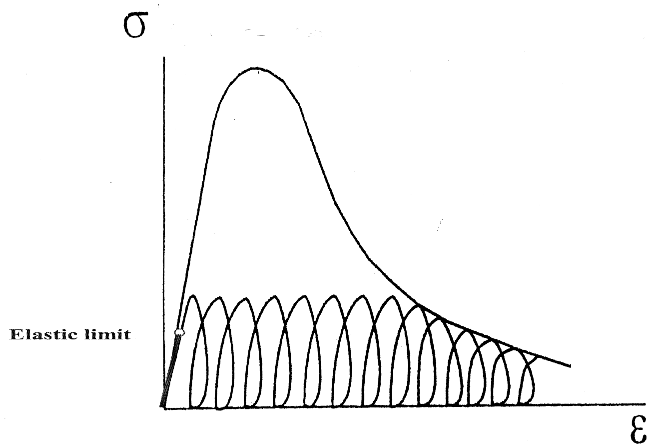

Figure 11: Schematic representation of damage development due to a repeated load.

Figure 11 shows the stress – strain curve as obtained from a failure test and the stress – strain loops due to a number of load repetitions. The figure shows that even if the stress level in the asphalt sample is less than the apparent strength of the material, the repetition of loading can lead to failure. As shown in figure 11, during cyclic loading plastic strain accumulates, so the state of stress gradually approaches the monotonic envelope. When it touches this envelope, the material starts to degrade rapidly. This principle is used for the damage analysis of a pavement structure loaded by a B 777 wheel configuration.

An example application of the ACRe model for asphalt concrete applied on an airfield pavement loaded by a Boeing B 777:

Since the influences of strain rate, temperature and state of stress are incorporated in the model, the behaviour corresponding to the conditions in any point of a construction can be determined automatically. As a result, the “weak spots” in any combination of geometry, material and loading will show up in an analysis, because they will be the first to show damage.

In order to show the capabilities of the model, a dynamic 3D finite element simulation using the ACRe-model in its current, prototype formulation, was run using the package CAPA-3D [6]. The load used was the six wheel bogie of a B777 (contact pressure 1.27 MPa) which was placed on a pavement consisting of 200 mm of asphalt (E = 3000 MPa), on a 400 mm thick base layer (E = 300MPa) on a subgrade with a modulus of 100 MPa. The damage analysis was only made for the asphalt layer since only for those materials models as described above are available.

The load was a repeated load which “patted” the pavement at a fixed position. The duration of each load pulse was 0.5 s.

Damage was defined as the square root of the sum of the squares of the permanent strain components (Equation (6)). Since the test programme is still underway, the model parameters are based on incomplete data and should be considered as preliminary values. For this reason, the actual values are not of real interest in this simulation but the overall pattern is.

$$e_{eq} = \sqrt{(e_p^{xx} \cdot e_p^{xx} + e_p^{yy} \cdot e_p^{yy} + e_p^{zz} \cdot e_p^{zz} + e_p^{xy} \cdot e_p^{xy} + \ldots)} \tag{6}$$

Where: e_p^{xx} = plastic strain in the x direction

Figure 12 shows the load configuration while figure 13 shows the damage initiation and progression along line 1 (see figure 12). It should be noted that figure 13 only provides information on the damage in the asphalt layer. The left hand side of figure 13 shows the development of the deviatoric damage while the right hand side shows the development of the total damage which is the sum of the deviatoric and volumetric damage. From the damage figures given in the figure it can be concluded that the volumetric damage is dominant over the deviatoric damage. The volumetric damage is clearly due to the bending of the pavement. Separate plots can be made which show whether this damage is tensile or compressive. Lack of space pre-vents these pictures to be shown. Furthermore one can observe that the damage is developing over a large area. The influence of the individual wheels cannot be observed as would be the case when a linear elastic analysis was performed and one was only interested in the tensile strains (see e.g. figure 1). This implies that, for this example, one should analyse damage in terms of aircraft passes rather then in terms of wheel passes.

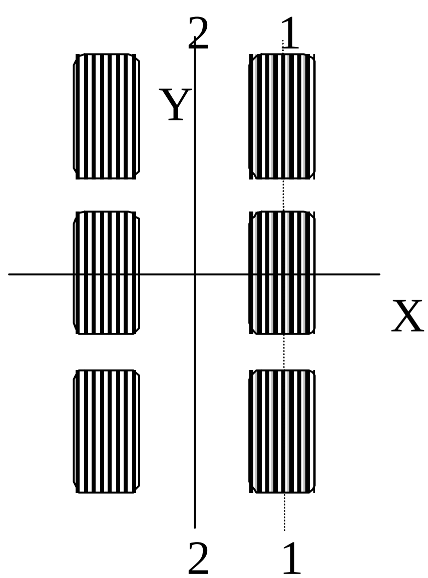

Figure 12: Load configuration.

Figure 13 indicates that the highest total damage develops at the top of the asphalt layer. One should realise however that damage is defined here as the square root of the sum of the squares of the permanent strain components. This means that the damage as defined here should not be confused with visible damage. In order to obtain information on the visible damage, the volumetric damage, that can be calculated from the difference of the total and deviatoric damage, should be split in damage due to volumetric tension and volumetric compression. It is a well known fact that asphalt mixtures are more sensitive to tension than to compression. This implies that the same calculated value for the volumetric tension damage (in terms of plastic strains) as for the volumetric compression damage means that more tension damage (cracks) than compressive damage (deformations) will be visible.

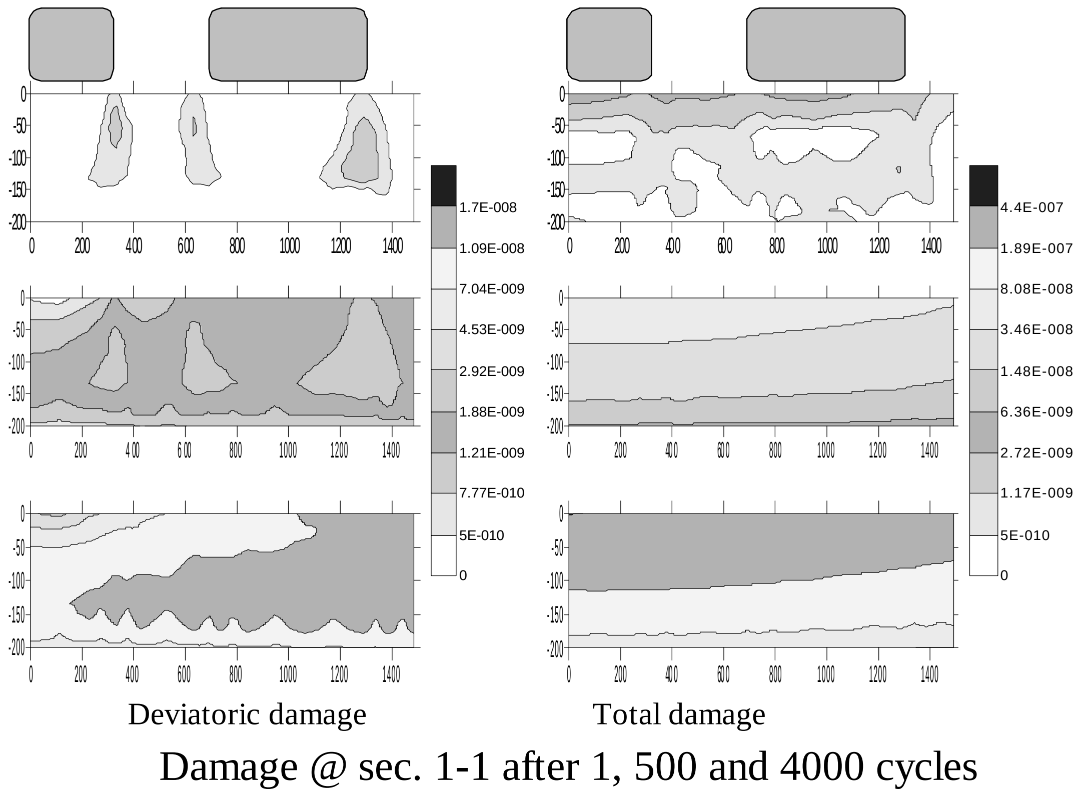

Figure 13: Damage development after 1 cycle (top left and right hand figure), 500 cycles (middle left and right hand figure) and 4000 cycles (bottom left and right hand figure).

For the sake of completeness it is recalled that the analysis is based on the materials characteristics derived from the test results shown in figures 7 and 10. It is emphasised that these test results describe the behaviour of the material under both low stress, low strain conditions as well as under high stress, high strain conditions.

Furthermore it should be mentioned that an analysis as presented here can be performed for any type of asphalt mixture provided that the material characteristics are available. It is therefore possible to analyse, e.g., the effect of aging as well as the effect of polymer modifications.

The reader might be confused by the terms deviatoric and volumetric damage. These damages can be described as follows. Deviatoric damage is the damage related to a change in shape of a volume element; shear stresses cause such a change in shape. Next to deviatoric damage there is volumetric damage which is related to a change in volume of a volume element. This change in volume is related to tensile or compressive stresses. The total damage is the sum of the deviatoric and volumetric damage. This is schematically shown in figure 14.

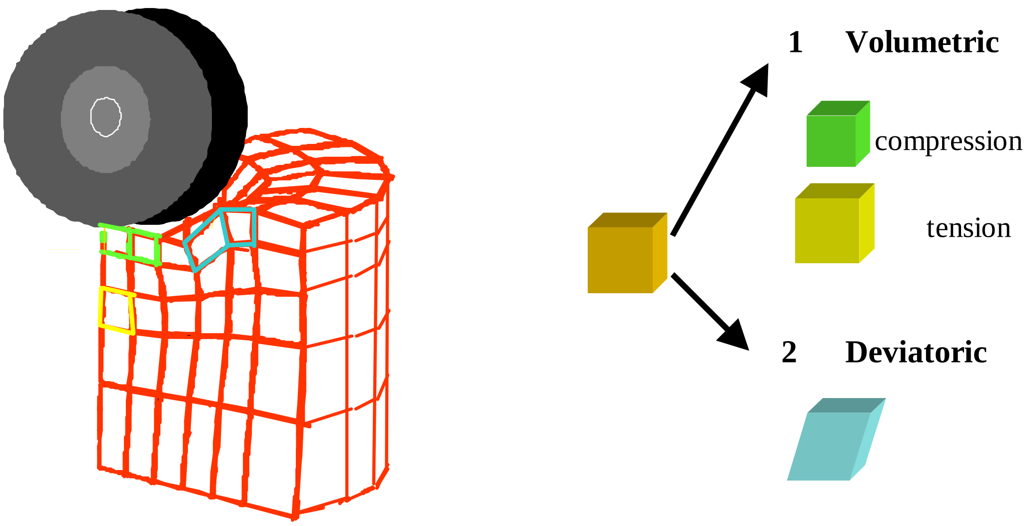

Figure 14: Schematic representation of volumetric and deviatoric damage.

For the interested reader it is mentioned that the time involved to do the analysis as described above took a calculation time of 5 days. It is clear that this analysis time is too long to be acceptable for practical purposes in solving day to day days problems. The running time is however thought to be acceptable for the special problems as described in this paper.

It is believed that by means of the model presented in this paper a much more realistic picture of damage initiation and progression due to complex multiple aircraft loading gears is obtained than could be obtained using the well known linear elastic multi layer approach. It is also believed that the model presented is an excellent tool in analysing and comparing the damaging effect of various aircraft.

Conclusions:

Based on the work presented in this paper, the following conclusions can be drawn:

a. Commonly used linear elastic multi layer analyses that use the maximum tensile strain as an indicator for the damage resulting from a passage of a heavy aircraft with a complex multi wheel configuration are insufficient to calculate the damaging effect of such configurations.

b. For asphalt mixtures, non linear elasto-visco-plastic models capable of describing the pre and post peak load (failure) behaviour of a sample when subjected to a 3D state of stress, such as the one presented in this paper, can be used very well to analyse the effect of multiple wheel configurations.

c. The parameters of such a model can be obtained from compression and tension tests.

d. The example has shown that damage initiates and progresses as a result of an aircraft passage rather than as a result of individual wheel passes.

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